Remarks/Arguments:

Claims 9-20 are pending in this application, as this Amendment cancels withdrawn claims 1-8 and 21-27. In the Office Action dated August 24th, 2005, the Examiner has allowed claims 9-20, and has requested correction of two formal matters: cancellation of withdrawn and un-examined claims, and correction of the drawings to reflect reference number 10. The withdrawn claims 1-8 and 21-27 are canceled, leaving only allowed claims 9-20.

The attached Replacement Sheet adds reference number "10", as supported at page 5 lines 19-20 of the written description. MPEP 608.02(v) provides that an annotated sheet is not required for mere addition of reference numbers. No new matter is added.

Further, the Applicant requests that the Examiner annotate the record that all references submitted by the Applicant have been considered. Specifically, the PTO 1440 submitted with the application lists under the heading "Other Documents" a reference entitled: "Fluxless High-Vacuum Packaging MEMS and IR Sensors". While other references listed on that PTO 1440 are checked as considered, that reference is not. Another copy of that reference in six pages is attached hereto for the Examiner's convenience. Additionally, the Applicants submitted on September 15, 2005, an IDS listing five documents disclosed by the International Searching Authority for a related PCT application, including:

US Pat. No. 5,433,639 by Zahuta et al;

US Pub. No. 2002/0175284 A1 by Vilain;

US Pat. No. 6,479,320 B1 by Gooch;

Japanese publication no. JP 09229765 by Yasuo (English abstract); and

PCT publication WO 02/39481 A2 by Ouvrier-Buffet.

As these references were timely submitted, the Applicants respectfully request that the Examiner consider all six of the above references against claims 9-20 and annotate the record as appropriate.

The undersigned representative welcomes the opportunity to resolve any matters that may remain, formal or otherwise, via teleconference at the Examiner's discretion.

Respectfully submitted:

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CERTIFICATE OF MAILING

I hereby certify that this correspondence is being deposited with the United States Postal Service as first class mail in an envelope addressed to: Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.

2005-11-21
Date

W.C. Schult
Name of Person Making Deposit

AMENDMENTS TO THE DRAWINGS:

Please replace drawing sheet 1/4 bearing Figure 1 with the attached "Replacement Sheet", also bearing Figure 1.

The attached Replacement Sheet adds reference number "10", as supported at page 5 lines 19-20 of the written description. This is in response to the objection cited in the referenced Office Action. No new matter is added. An annotated sheet is not seen as required per MPEP 608.02(v).

SST International

"World Class Leader in Package Assembly"

Fluxless High-Vacuum Packaging of MEMS and IR Sensors

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Abstract

Historically, infrared (IR) thermal imaging technology has been driven mainly by military applications. Based upon helium-cooled microbolometers, the cost and size of these systems have limited their use in many commercial applications such as automotive night-vision enhancement, firefighting, and security systems. Advances in microbolometer technology have brought forth the development of Uncooled Focal Plane Arrays (UFPAs) designed to operate at room temperature, eliminating the need for super-cooling and thereby significantly reducing the cost and complexity of the overall system package. Although uncooled technology will inherently reduce package dimensions, the semiconductor detectors must still be hermetically sealed in a high vacuum environment to maximize the thermal sensitivity of the microbolometer. The timely process of sealing these UFPAs within a high vacuum has traditionally been the largest limiting factor on package throughput. Current technology requires that each pre-assembled package be individually mounted to a high-vacuum pump via a pinch-off tube and vacuum baked for a number of days before activation of the getters and final pinch-off seal. In an effort to meet the demand of increasing volumes, a novel batch-type packaging approach has been proposed which combines a high-vacuum bakeout, activation of getters, and fluxless hermetic package assembly into a single, semi-automated in situ process, significantly reducing the overall cycle time of the sealing process.

Key words: microbolometer, IR sensor, high-vacuum packaging, getter, fluxless soldering, hermetic

Introduction

Until recently, the high cost of infrared thermal imaging systems has limited their use to mainly military applications. Infrared sensors have been employed in thermal weapon sights, night-vision goggles, missile seekers, driver viewer aides, and reconnaissance and surveillance systems. Incorporating the use of materials like mercury, cadmium and tellurium, traditional systems are based on cryogenically cooled, narrow-band gap semiconductor detectors [1]. Recent advances in microbolometer technology have resulted in the conception of Uncooled Focal Plane Arrays (UFPAs) designed to operate at room temperature. Without the need for expensive, relatively heavy, cryogenic coolers and associated packaging, cost and weight will be reduced dramatically [2]. This reduction in weight and cost will inherently open the door for many commercial applications of these detectors such as firefighting, process control, medical imaging, navigation, forest fire protection, gas detection and analysis, security monitoring, and most importantly, automotive night-vision enhancement. This latter application, although current volumes are low, could potentially define a huge market. As such, a low-cost, high-volume packaging approach will need to be realized to meet these future demands.

What is a Microbolometer?

A microbolometer is a micromachined detector in which absorbed infrared irradiation is detected as a temperature change by using a temperature sensitive resistor [3]. To maximize the sensitivity of the detector, the microbolometer must be isolated in a hermetic package under high vacuum to minimize gaseous heat transfer within the sealed package. If the pressure surrounding the microbolometer is too high, the gas provides a thermal conduction path between the silicon substrate and the bolometer bridge, effectively shorting out the signal. Even though reliable, high-vacuum packages have been made for years, the packaging process (cleaning, assembly, pumping, baking, getter firing, sealing) and required materials add significant cost and weight.

Traditional Packaging Techniques

Traditional packaging technology requires a two-step process whereby package assembly is carried out separately from other operations such as vacuum baking, getter firing and final pinch-off seal. First, the detector, or microbolometer, must be mounted in a metal/ceramic dewer and the assembly (base, lid and IR-transmitting widow) sealed via a solder reflow or seam seal operation. Once the package has been leak checked to ensure hermeticity, the package is then mounted to a high-vacuum pump via a pinch-off tube and baked out at as high a temperature as allowed by the temperature-sensitive components. The overall throughput of this operation is limited by the capacity of the pump and multi-day bakeouts are usually required to obtain the desired vacuum levels [4]. When the internal pressure of the package reaches the minimum vacuum level required for getter activation, the getter(s) within the package are fired via a thermal or electrical activation sequence. After completion of the getter activation step and final pump down, the package is sealed using the copper pinch-off tube. It has been determined that the largest limiting factor on package throughput is the need to individually mount package assemblies onto pump ports for the evacuation process prior to the final seal.

Package Requirements

As stated previously, semiconductor microbolometers must be hermetically sealed in a vacuum to provide the necessary thermal isolation to the detector. It has been reported that modern uncooled IR sensors require a vacuum level of 50 mTorr or less in order to avoid loss of sensitivity due to thermal heat transfer through the gas within a package [5]. Not unlike the majority of other Micro-Electro-Mechanical-Systems (MEMS), cavity hermeticity is very critical in protecting the fragile microbolometers against contamination from the atmosphere, dirt and moisture, as well as from mechanical and radiation loads. The package must be sealed in a contaminant-free environment, therefore eliminating the use of flux during the reflow process. The overall reliability of the system package will be determined by how well these considerations are met and maintained throughout the lifetime of the package.

Solder Selection

Due to inherent temperature restrictions related to most microbolometer assemblies, various low-temperature, indium-based solders have been evaluated for use in the package assembly. Depending upon the composition, melt temperatures for these alloys range from 16°C to 300°C. Since hermeticity is critical to this application, stress cracking within the solder joint and along the joint interface induced by thermal cycling must be minimized. Indium-based alloys exhibit excellent thermal stress characteristics and therefore make ideal solders for joining materials with large CTE mismatches [6].

Indium was also chosen for this particular application due to its low interaction rate with expensive, gold metallizations. When molten indium comes into contact with a gold-metallized surface, a high-melting point interfacial layer of AuIn2 intermetallics is formed between the bulk solder and metallization, thereby preventing further dissolution of the gold material [7]. Since these hard intermetallics are usually suspended within a pliable matrix, the resulting intermetallic layer is relatively ductile and does not impart any brittle properties to joint. This low scavenging rate of gold allows for excessive temperature excursions above the liquidus point of the solder to enhance wetting without complete dissolution of the gold metallization.

Getters

Throughout the lifetime of a vacuum-sealed MEMS device, the vacuum level will be degraded due to outgassing of common atmospheric gases from the surfaces within the package and by diffusion and/or microleaking through the cavity walls. To maintain the required vacuum levels during the lifetime of the package, these gases must somehow be removed from the atmosphere within the sealed cavity. In such cases, materials called "getters" are routinely employed.

Constructed from elements such as zirconium, aluminum, vanadium, and iron, a "getter" is a material which chemically sorbs active gases in a vacuum environment [8]. Simply put, they are mini vacuum pumps designed to absorb specific gases. To activate these getters, the getter material must be heated to some given activation temperature for a specific period of time to remove the thin oxide layer that exists on the surface of the getter after being exposed to ambient atmosphere.

Depending upon the specific application and package design, getters can be activated either thermally, by heating the entire package to the activation temperature, or electrically, by selectively heating the getters via resistive heating of the getter substrate. In certain cases, heating the entire package may have adverse effects on materials, plating, solders, and most importantly, temperature sensitive MEMS devices with protective anti-reflective coatings. In these cases, electrical activation is ideal where only the getter material is directly heated by

passing a known current through the resistive getter substrate.

High-Vacuum Systems

Normal pressures in a "high-vacuum" system range from 10^{-4} to 10^{-7} Torr. To obtain these levels on a consistent and timely basis, it is crucial to understand what factors will affect the pumping speed and ultimate pressure of a given system.

There are four main types of pumps used in traditional high-vacuum systems: diffusion, turbomolecular, ion and cryogenic. Each type of pump has qualities specific to their application and intent of use. Compression ratios between these pumps will vary for each particular gas considered. For the experiments described in this paper, a turbomolecular drag pump, backed by an oil-free, piston-type roughing pump, was incorporated in the vacuum system.

Today's turbomolecular pumps can produce high pumping speeds, large hydrogen compression ratios, and low ultimate pressures. They do not backstream hydrocarbons from the lubricating fluid or mechanical pump and are well suited to pump gas cleanly at high flow rates or low pressures [9]. To maximize the pump's performance, it should be connected to the vacuum chamber with minimal conductance losses.

Materials within the high-vacuum chamber as well as the materials used to construct the chamber will have a large impact on pumping speeds and ultimate vacuum levels. All materials used within the system should have low outgassing rates and low permeability to the lighter gases such as hydrogen and helium. For this reason, most high-vacuum chambers are manufactured from TIG-welded 300 series stainless steel with elastomer and/or metal gasket sealed flanges.

One of the most important factors affecting the performance of vacuum systems, whether low-vacuum, high-vacuum, or ultrahigh-vacuum, is the amount of water vapor adsorbed on all surfaces within the chamber. Figure 1 shows a residual gas analyzer (RGA) scan of a high-vacuum system during the initial stages of pump down. Notice the large peak at mass 18 and the two smaller peaks at masses 16 and 17. These peaks represent residual water molecules and their constituents within the system, respectively. The scan also shows traces of hydrogen, nitrogen and carbon dioxide as would be expected.

Although highly polished stainless steel has excellent desorption qualities, it will nevertheless re-adsorb water whenever exposed to air. To minimize water adsorption, the chamber should be flushed with a dry, inert gas whenever it is exposed to ambient atmosphere. Since the desorption of water vapor and other gases is greatly temperature dependant, heating the walls of the chamber will increase the removal rate. All other materials within the vacuum chamber such as tooling and package components will also adsorb water when exposed to ambient and should be kept as clean and dry as possible. Pre-drying process materials in a standard low-vacuum furnace will minimize pump down times in the process chamber and therefore reduce overall cycle times.

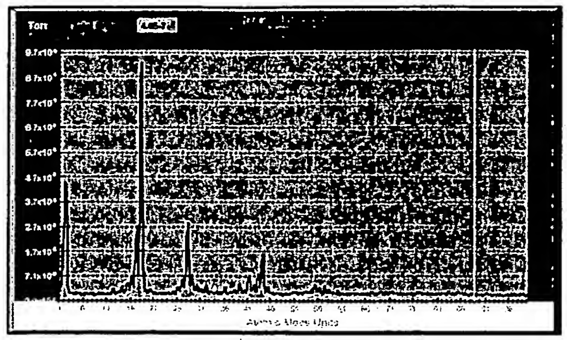

Figure 1 - RGA scan of high-vacuum system during the initial stages of pump down.

Process Chamber

The process chamber is cylindrical in shape, approximately 30cm in diameter and 30cm deep. The walls of the chamber are constructed from type 304-polished stainless steel to minimize the adsorption of water and other atmospheric gases. All of the feed throughs incorporate the use of metal gasket flanges to maintain a high-vacuum seal. Two, hermetically sealed, gold-plated, copper electrodes extend from the chamber floor to feed electrical power to the resistive graphite tooling. A turbomolecular drag pump is attached to the sidewall of the chamber with little or no conductance losses by way of a 7cm long by 15cm diameter stainless steel tube. A pneumatic actuator with an attached "lift plate" protrudes from either the bottom or the top of the chamber providing motion to the moveable plate of the tooling assembly. In this way, various components of the package assembly can be separated at any portion of the cycle to minimize conductance losses from the inside of the package to the entrance of the turbomolecular pump.

A water-cooled, ceramic contact block and multiple-circuit hermetic feed through are installed at the base of the chamber. A specified number of spring-loaded contact pins, better known as "pogo pins", positioned within the contact block, make the connection to multiple power supplies which provide the necessary voltage/current to activate the getters

during the cycle. All of the process parameters such as time, heat, vacuum, pressure, lift actuation and getter activation current levels are controlled through a distributed logic system that links intelligent external controllers to a centralized PC running on Windows 2000. Figure 2 gives a top view of the process chamber showing the contact block, vacuum pump port and gold-plated electrodes.

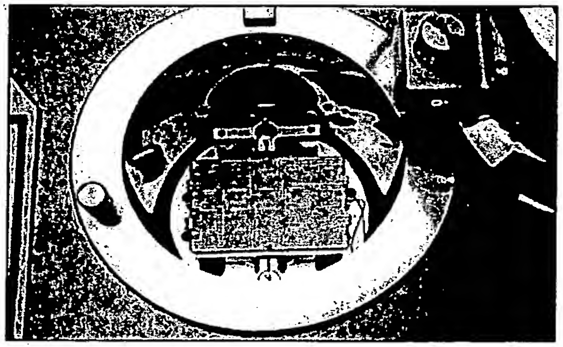

Figure 2 - Top view of process chamber showing the contact block, vacuum pump port and gold-plated electrodes.

Graphite Tooling

The graphite tooling serves dual functions as a fixture to locate and maintain components in their desired positions and also as a resistive heat source. Graphite is relatively inexpensive, easy to machine, resistant to creep, has excellent thermal properties and is not wetted by the majority of solder alloys [10]. The graphite used is a semiconductor grade, isotropic material where the grains are uniform in all directions. This is critical since any variation in graphite density may affect the thermal gradient of the tooling within the workspace. Figure 3 shows an infrared image of the minimal thermal deviation in a standard tooling configuration.

Since the sealing process takes place in a high vacuum atmosphere, it is important to note that the major mode of heat transfer is conduction directly from the graphite surface to the piece parts. At pressures below 760 mTorr, heat transfer throughout the atmosphere within the chamber virtually stops [11]. As such, the components must be in intimate contact with the tooling to provide a uniform heat distribution.

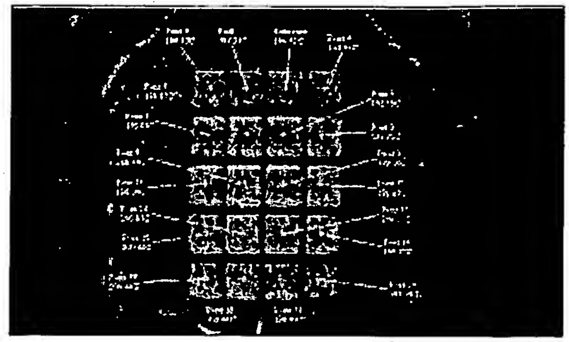

Figure 3 - Infrared image of a standard tooling configuration.

The tooling assembly consists of three graphite plates stacked together to form a stack-up tool. The bottom plate, or "boat plate", contains multiple cavities of some given depth and dimension that locate the ceramic/metal base with microbolometer attached. The middle plate, or "moveable plate", holds the lid/window assembly and can be moved up or down between the boat and heat plate during the cycle. The top plate, or "heat plate", is connected to the boat plate via graphite spacers on either end of the tool. The heat plate serves as a heat source for the moveable plate when it is in the upward position and also acts as a locating tool for weights used to apply compressive forces to the assembly during reflow. Figure 4 shows a cross section view of the tooling assembly.

Carbon coatings are applied to the graphite tooling to reduce particulates, enhance thermal and electrical uniformity, reduce porosity and minimize outgassing of the material. It is important that these coatings match the CTE of the graphite, thereby preventing cracks that may cause localized heating and lead to thermal gradients across the workpiece.

Copper and/or stainless steel retainers are used at both ends of the tool as an interface material between the graphite plates and the copper electrodes. The thermal properties of these retainers will affect the ultimate obtainable cooling rates of the fixturing.

Proposed Process

The process begins with the mounting of the microbolometer and associated electronics to the package base. Since the internal cavity pressure of the assembled package is critical to it's functionality, it is essential to minimize any materials which may outgas during processing or the lifetime of the package. Therefore, materials such as adhesives and epoxies should be avoided.

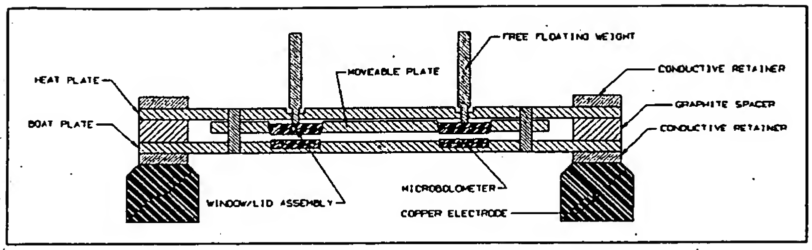

Figure 4 – Cross section of tooling assembly.

Clean, dry, solder preforms are then attached to the necessary components of the assembly using a tack-welding operation. With the detector, associated electronics and solder preforms in place, the package base and lid/window assembly are loaded into the appropriate cavities in the graphite tooling. It should be noted that at this point, the moveable plate is referenced to the upward position, thereby leaving a separation gap of approximately 1-2mm between the package base and the lid/window assembly. The tooling is then placed in the reflow chamber and the pre-programmed profile is initiated.

The cycle begins with a "continuity check" which determines whether or not all getter circuits are continuous, and if not, which getters will not be capable of activating. If any of the circuits are not continuous, the operator may decide to abort the cycle at this point and take corrective action. Once the continuity check is complete, the thermal cycle begins with an extended vacuum bakeout at an elevated temperature to remove as much water vapor and other atmospheric gases from the closed system as possible. In a vacuum chamber the volume gas is removed first, followed by surface desorption, out-diffusion from the solid, and last, permeation through the solid wall. All of these processes except volume gas removal are greatly temperature dependent [12].

Although the graphite tooling, reflow chamber and/or package components may have been vacuum baked prior to the loading of the tooling, water vapor will usually be the predominant gas within the reflow chamber atmosphere and will dictate pump down speeds. Since water molecules are polar by nature, they have a high affinity for adsorbing to any surface within the chamber. Any residual water left on the components prior to the final seal will reduce the reliability and lifetime of the package. Therefore, the vacuum bake will continue for a predetermined amount of time which has been deemed sufficient to remove the majority of water vapor from the system. After completion of the initial vacuum bake, the fixturing is allowed to cool to a given temperature for the getter activation sequence.

Assuming a chamber pressure of less than 10^{-6} Torr [13], current is supplied to the getter(s) within the package via the pogo pins to activate the getters. The amount of current applied to each getter is controlled by individual power supplies which apply the necessary voltage to obtain a specified current level. The getters are resistively heated in this way to some predetermined temperature for a given period of time. At this point, the getters are now actively absorbing gases within the chamber.

The reflow cycle commences with a steady, pre-programmed ramp to the specified reflow temperature. During the temperature rise and prior to reaching the solidus temperature of the particular solder in use, the lift plate within the chamber is activated and the package base and lid/window assembly are brought into intimate contact for the final package seal. The temperature of the tooling continues to rise until the ultimate reflow temperature is obtained. Figure 5 shows a plot of temperature vs. time and pressure vs. time for a typical sealing cycle.

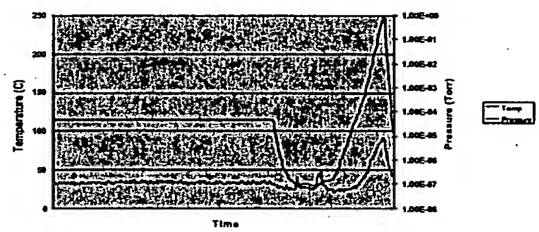

Figure 5 - Temperature and pressure plot of a standard reflow profile.

After allowing the solder sufficient time at the reflow temperature to wet out completely and form a hermetic seal, the heat is shut off and the cooling cycle commences. Cooling rates are maximized through water-cooling of the copper electrodes in contact with both ends of the graphite fixture. As the temperature of the tooling drops below the solidus point of the solder, the vacuum is shut off to the chamber and a steady flow of nitrogen gas is introduced to expedite the cool down.

Initial Results

Preliminary experiments have shown excellent feasibility for the proposed process and tooling arrangement. Chamber pressures below 10^{-7}

Torr were obtained during the experimental trials. Hermetic assemblies have been manufactured and tested for image quality and corresponding vacuum levels obtained. Cavity pressures below 10^{-4} Torr have been obtained with the use of nonevaporable getters. Further studies will need to be performed in an effort to quantify package qualities including overall cavity pressure, leak rates and package vacuum life.

Conclusion

Due to the ever-increasing commercial applications of IR sensors, a low-cost, high-throughput process must be realized. In an effort to meet these demands, a batch-type packaging approach has been presented which combines multiple processing steps into a single, semi-automated in situ process. The proposed packaging approach has many advantages over traditional methods. Cycle times are reduced due to the elimination of pinch-off tubes and required processing techniques. Less handling of the fragile sensors is required since package assembly and vacuum bakeout are performed in a single step. Multiple assemblies can be processed at one time, thereby increasing throughput. Process control is maintained through the repeatability of the computer-controlled system.

Although there are still technical challenges to the packaging approach, most of them stem from material related issues. Once these issues are addressed, the average consumer will begin to benefit from the many new applications of IR technology.

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